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Optimisation of a cogenerated energy systems: the cane biomass flexi-factory case study

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Abstract

Mauritius has a long tradition of using cogeneration systems for electricity generation. Bagasse, a by-product of sugar cane is burnt in high temperature and pressure boilers to produce superheated steam to be used for combined heat and power generation. Steam is fed in condensing extraction steam turbine coupled with an alternator to produce electricity and the exit low pressure steam of the turbine is used for the processing of sugar with flexibility to be employed also in distillery and refinery activities. Multi-criteria analysis of such bio-refinery inputs and outputs is conducted considering Energy, Engineering, Economic, Environmental and Ethical dimensions like sustainability, equity and democratization of the energy sector. Due to the reduction of price obtained for the sale of sugar to the European Union, the sugar industry has to re-engineer itself to move towards the flexi-factory concept for its survival. Production of high value-added refined sugar/special sugars, dehydrated ethanol for transport and power use and green electricity are constrained by a host of factors from climatic conditions to the price of sugar on the world market through the grid power costs itself dependent on world oil and coal prices. Environmental standards are also to be considered. The aim of this paper is to optimize the cogenerated energy systems of the cane flexi-factory by a holistic energy systems analysis. Actual parameters of a flexi-factory are used to calculate the energy efficiency of each components parts of the system as well as social, economic and environmental benefits. Policy implications crucial to the future viability of such complex energy systems; these are fully discussed in relation to national and international objectives.

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Keywords: cogeneration; energy efficiency; sugar cane; bio-energy; flexi-factory

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1. Introduction

The biggest challenge facing energy industries is to satisfy the ever increasing demand of energy without destroying the environment [1]. Current energy systems using fossil fuels are not sustainable, hence alternative clean energy sources are being looked into. Renewable energy is therefore being promoted specially those harnessed from biomass, that is, bio-energy. Biomass is obtained from forests, agriculture and wastes in solid, liquid or gaseous states. The share of biomass based electricity is about 2% of the total electricity generation in the world [2]. Biomass is mostly combusted in furnace-boiler system to produce steam for electricity production. In the cane industry, sugar cane biomass also called bagasse; a by-product of sugar cane is burnt in high temperature and pressure boilers to produce superheated steam to be used for combined heat and power generation. The heat is used to convert sugar cane juice to either sugars or ethanol. The power generated is used for sugar mills consumption and the surplus is being exported to the national grid. The process of simultaneous production of heat and electricity from a single source is called cogeneration. The efficiency of a cogeneration plant is higher than those achieved when heat and power are produced separately [3]. In fact, cogeneration systems can reduce the demand for the fossil fuels up to 35% compared with conventional systems [4]. But, for cogeneration systems to be applicable in an industry, both heat and power must be utilized, this is so for the sugar cane industry.

Sugar cane is produced in over 100 countries worldwide [2] and the sugar cane production in the world was about 1.7 billion tonnes in 2012 [5]. In Mauritius, sugar cane was successfully cultivated since 1639 due to its suitable climate and land conditions [6], and since then the sugar cane industry was the main pillar of the Mauritian economy. This industry has also benefited from a special agreement with the European Union(EU) for the sale of sugar at a favorable guaranteed price which has helped the country to sustain its economy. Moreover, the sugar industry has a long tradition of using cogeneration systems for electricity generation. In 1957, Mauritius being the first country in the world to have started the production of electricity using cane biomass as fuel through a cogeneration system in a sugar mill. Presently, about 14% of the electricity supplied to the grid is generated from bagasse cogenerated systems in Mauritius [7].

In 2005, EU decided to decrease the price of imported sugar paid from African, Caribbean and Pacific (ACP) countries which are the sugar cane producers. The Mauritian Government devised a Multi-Annual Adaptation Strategy commonly known as the MAAS in the form of a ten year, 2006–2015, action plan [8]. The main objective of the MAAS is to ensure the commercial viability and sustainability of the sugar sector by providing a set of measures aiming at improving the viability of the sugar industry. These are: electricity production from biomass, centralization of sugar mills to increase productivity, production of dehydrated ethanol for transportation, fertilizers from cane wastes, carbon dioxide for the soft drinks industry, value-added commodities such as refined sugar, power use and green electricity. In fact, the sugar industry may contribute positively towards climate change mitigation and improve the energy security of a country [9]. The Mauritian sugar industry has re-engineered itself to move towards the flexi-factory concept for its survival. The price of electricity produced by sugar mills owners, called the Independent Power Producers (IPPs) is tagged on the price of oil/coal in the international market. This has encouraged sugar mills owners to modernize and increase the capacity of their power plant annexed to sugar mills. Coal is being used during the intercrop season as cane biomass is available only during the harvesting season. IPPs electricity generation to the national grid is used as based load supply in Mauritius [10].

The flexi-factory is also called bio-refinery which is similar to petro-refinery. A bio-refinery uses biomass to produce transportation fuel, electricity, food and other high value chemicals [11]. The bio energy systems have lower greenhouse gas (GHG) emissions compared to fossil energy ones [12] and is considered as the main alternatives to mitigate GHG emissions [13]. Cherubin [10] concluded that biomass energy potential is maximized if a bio-refinery approach is adopted. Bio-energy provides 13% of energy demand in the world whilst in Africa it satisfied about 39% of total energy demand [14]. For a flexi-factory to be sustainable, both heat and electricity, obtained from the biomass should be internally used for other processes/systems such as for distillery and refinery purposes [1]. The flexi-factory model is being promoted in the cane industry in Mauritius. Nguyen et al. [12] concluded that energy obtained from sugar cane would contribute a substantial reduction in fossil fuel utilization through the use of bagasse for electricity generation and ethanol for transportation purposes. However, the reduction potential depends on the optimal use of sugar cane. Dias et al. [15] simulated that the higher production of ethanol in a cane biomass flexi-factory, the higher will be the CO_2 avoided. This is because the ethanol obtained could be blended up to a proportion of 85% with gasoline and use as fuel in cars which is a practice in Brazil. Transportation emits about 20-25% of the total CO_2 emissions in Europe and Mauritius [16,17]. The share of biofuels is less than 2% of the global transportation fuels needs. So, there is a great potential to increase this share through the production of dehydrated ethanol for transportation use.

Steam, obtained from the combustion of bagasse, is fed in condensing extraction steam turbine coupled with an alternator to produce electricity and the exit low pressure steam of the turbine is used for the processing of sugar with flexibility to be employed also in distillery and refinery activities. The energy obtained from sugar cane cogenerated systems is both a renewable and sustainable energy which could be utilized by the present generation without causing harmful repercussions for future generations [18]. If sugar cane is fully exploited, it could increase its market share of global supply of energy in a sustainable manner [1]. Demirbas et al. [14] reported that the potential market of biomass could increase up to 50% of the world energy use. The outputs of the cane biomass flexi-factory are however constrained by a host of factors from climatic conditions to the price of sugar on the world market through the grid power costs itself dependent on world oil and coal prices. Moreover, environmental standards are also to be considered.

The aim of this paper is to optimize the cogenerated energy systems of the cane flexi-factory by a holistic energy systems analysis. A successful optimization of a system can result in significant energy and cost savings as well as a reduction in the CO_2 emissions [19]. Actual parameters of a flexi-factory are used to calculate the energy efficiency of each components parts of the system as well as social, economic and environmental benefits. Multi-criteria analysis of such bio-refinery inputs and outputs is conducted considering Energy, Engineering, Economic, Environmental and Ethical dimensions like sustainability, equity and democratization of the energy sector. However, policy implications are crucial to the future viability of such complex energy systems; these are fully discussed in relation to national and international objectives.

2. Flexi-factory in Mauritius

Fig. 1 shows the four main components of existing flexi-factory in Mauritius - the sugar mills, ethanol distillery, sugar refinery and the cogeneration power plant. Cane is harvested in the sugar field and transported to sugar mills. The sugar cane is then milled, cane juice and bagasse, a residue of sugar cane are obtained. The bagasse is then fed to the high pressure and temperature boiler of an annexed cogeneration plant. Superheated is produced and fed to a condensing extraction steam turbine coupled with an alternator. The turbine has two exits. In the first exit, low pressure steam is obtained and exported to the sugar mills for the processing of cane juice to sugar mill, ethanol distillery to produce anhydrous ethanol and also for the processing of raw sugar to refined sugar. Hot water is obtained in the second exit, this is cooled down through a cooling tower and fed to the boiler to produce steam. Moreover, molasses, a by-product of sugar cane juice is obtained during the processing of sugar cane juice to sugar. Part of molasses produced is used by the Liquors and Rum Industry for the production of alcoholic drinks and the rest are converted to bio-ethanol through a distillery plant. The ethanol produced will be either exported or blended with gasoline up to a proportion of 10% to be used as fuel in motor vehicles. Vinasse, a process residue obtained during the process of converting molasses to ethanol, could be then converted to fertilizers through a Concentrated Molasses Solids (CMS) fertilizer blending plant. The fertilizers will be used for the cultivation of sugar cane.

Harvest of sugarcane is normally done from July to December. Thus, electricity and heat are obtained for the production of raw sugar during that period. However, the refinery and the distillery operate the whole year for the production of refined sugar and bio ethanol respectively. As a result of this new business model of the cane industry, heat and electricity are needed for the whole year. Before sugar cane industry, now called the cane industry, used coal during the off crop season to generate electricity which was then sold to the national grid through favorable power purchasing agreement with the Central Electricity Board (CEB), the sole body authorized to sell electricity to consumers. But now, due to the continuous operation of the other components of the flexi-factory, the distillery and the refinery, additional heat and electricity are needed during the harvesting period and off crop season. Thus, coal is used as fuel to produce heat and electricity. The heat and electricity is used by the refinery and the distillery whereas the excess electricity is exported to the national grid.

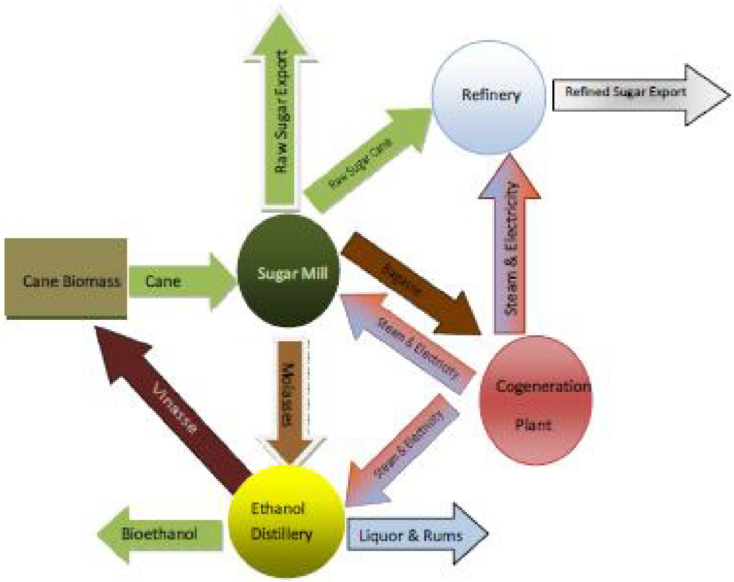

Fig. 1 : The flexi-factory in Mauritius[20]

Since 2006, due to the unfavorable price obtained from European Union for the sale of sugar, more and more land under sugar cultivation are abandoned as it is not profitable for the planters. About 2000 hectares of land under sugar cane cultivation are converted to residential plots, shopping malls or simply abandoned. So, if this trend continues, the cane industry will be at stake. It will no longer fulfill its contracts towards the European Union for the sale of sugar and towards the CEB for the sale of electricity as less bagasse will be available. Due to the modernization of the cane industry through incentives given by the government for the closure of non performing sugar mills and favorable power purchasing agreement with the sugar mills owners, only five sugar mills annexed with power plant are now operational. There were 11 sugar mills in the twenties. Moreover, during the past 20 years, higher pressure and temperature boilers with condensing extraction steam turbine(CEST) were commissioned in the Mauritian sugar mills thus leading to an increase in the production of electricity fourfold. However, during the past five years, bagasse –based electricity in the electricity mix is decreasing. The reasons for this decline were due to a decrease in land availability for sugarcane plantations, coupled with the fact that no investment has been made by IPPs to augment their capacity of their plants or to retrofit their boilers to higher pressure and temperature.

Table 1: Operating parameters of cogeneration plants in Mauritius [21]

Power Plant+ Sugar Mill	Operating Parameters	Effective Capacity(MW)	Surplus Exportable Electricity(kWh/tc)
Mill 1	82 bar/520 °C	62	100-120
Mill 2	82 bar/520°C	74	100-120
Mill 3	44bar/440°C	33	75
Mill 4	45bar/440°C	25.5	53
Mill 5	31bar/415°C	13	45

In 2013, there were 5 cogeneration power plants annexed to sugar mills into operation. Three of them operated during the whole year (continuous), they use bagasse during the harvesting season and coal during the off crop season. The fourth and fifth one operated only during the harvesting season (firm).

It is planned as from this year; the Mill 4 would cease to operate. Thus, all the cane harvested in the north, east, west and south region will be diverted towards Mill 1, Mill 3 and 4, Mill 5 and Mill 2 respectively.

3. Methodology

In this paper, the 5Es analysis (Energy, Engineering, Economy, Environment and Ethics) will be used to assess the performance of cogeneration systems [10]. The energy and the engineering are assessed by calculating the energy utilization factor and efficiency where as for the remaining 3Es a multi-criteria analysis is performed.

The energy efficiency indicator for the cogeneration plant will be the amount of kWh electricity generated per tonne of sugar cane (tc) crushed by the sugar mills. Moreover, the key performance indicators of the cane industry will be assessed such as: tonnes of cane harvested per hectare, electricity generated to the grid (kWh) per tonne of sugar cane or per hectares of land under sugar cane cultivation, litres of molasses per tonne of cane, litres of ethanol per tonne of molasses or cane. The input of the cogenerated system is the tonne of sugar cane milled, tonnes per hour of biomass fed in boiler whereas the output are: tonnes of raw and refined sugar produced, kWh of electricity generated to the grid, litres of molasses and vinasse obtained, and litres of ethanol produced.

To optimize the cane biomass flexi-factory with the decreasing land area under cane cultivation, different strategies/scenarios need to be designed. Operating boiler pressure and temperature, choice of biomass, selection of technology to convert sugar cane juice to sugar among others will have an impact on the output of the cane biomass cogenerated energy systems. Chatzimouratidis and Pilavachi [22] stated that the most important criteria for the evaluation of power plants are the technology used, economic aspects and the sustainability. The technology used has a direct impact on the output as well as on the cost of production. In addition, the sustainability and environmental impacts of a power plant depend on the choice of fuel used for the production of electricity. To decide on the best scenario which come closest to being affordable, environmentally clean and reliable, and socially acceptable, a multi-criteria decision analysis of the scenarios has to be carried out , using the following indicators such as energy security, ash disposal, greenhouse gas (GHGs) emissions, job security, health hazards risks, compliance with environmental law, capital expenditure, share of bagasse-based electricity in the electricity mix and revenues from bagasse-based electricity to assess the other 3 Es, that is, the Economy, Environment and Ethics.

4. Results and Discussion

4.1. Energy analysis

The cane industry is losing its land area under sugar cane cultivation by 2000 hectares annually. With this trend, it would be difficult to achieve the 17% share of bagasse-based electricity in 2025 as planned by the Long Term Energy Strategy for the period 2009-2025 of the Government in order to increase the share of renewable energy in the country electricity mix from 20% in 2010 to 35% in 2035 [23]. The share of bagasse-based electricity was expected to increase from 16% in 2010 to 17% in 2025.

The cane industry is at a cross road with decreasing price obtained for its sugar and decreasing land area under cultivation. So, new strategies/scenarios need to be designed to make the cane industry viable and sustainable. As from this year, an ethanol plant forming part of the flexi-factory will be operational using molasses for the production of bio ethanol. The total production of molasses is about 3% of the weight of the cane fed in the sugar mills. About 25ML of bio ethanol will be produced from 90 000 tonnes of molasses while the rest of the molasses will be used by the Alcohol and Livestock Feed industries. In this paper, scenario analysis was conducted with implementation of a 82bar/520°C bar or higher boiler operating parameters in all power plant annexed to sugar mills; use of sugar cane of higher fibre content; use of cane tops and leaves for the production of electricity; optimization of low pressure steam used for the conversion of sugar cane juice to sugar. Moreover, as the boilers of the cane industry are fed by coal during the off crop season to produce steam; another scenario could be the use of woody biomass as fuel in the boiler thus decreasing fossil consumption. Consequently, the share of renewable energy would increase in line with the Long Term Energy Strategy [23] and the vision of the Government to make Mauritius a sustainable island could be achieved.

Therefore, five scenarios were designed. This would help to identify possible output based on different inputs [1]. The scenarios are as follows: Scenario A: Implementation of 82bar/520^{0}C bar or higher boiler in all power plants; Scenario B: use of cane of higher fibre content; Scenario C: use of cane tops and leaves as fuel in addition to bagasse in boilers; Scenario D: optimization of low pressure steam in sugar mills; and Scenario E: a combination of scenarios A to D.

The energy efficiency of the flexi-factory for each scenario will be calculated and compared with the present case. Multi-criteria analysis will be used to assess the 3Es, that is, Environment, Economy and Ethics.

Scenario A: Implementation of 82 bar/520°C bar or higher boiler in all the power plants

Higher pressure and temperature boiler produces more super heated steam from bagasse to be fed in condensing extraction steam turbine. There are two main exits of the steam turbine. The first exit of low pressure steam is used by the annexed sugar mills, refinery and ethanol for the processing of: cane juice to sugar; from raw sugar to higher value added commodities such as refined sugar; and for the conversion of bio-ethanol for transportation use. Steam/hot water of the second exit is used for the generation of electricity. As the quantity of heat used by the sugar mills, refinery and ethanol is fixed, more steam is available for the production of electricity. The higher the boiler operating parameters, the higher will be the steam/bagasse ratio, hence more electricity will be generated. The generated electricity has increased from 56 kWh/tc to 87 kWh/tc, indicating a 55% increase, for the period 2003-2012 [24]. This is attributed to the centralization of the sugar mills from 11 mills to 5 mills and the implementation of the higher pressure and temperature, 82 bar/520°C boiler in two existing power plant annexed to sugar mills. It is to be noted that among all the four existing power plants, only two are equipped with 82 bar/520°C boilers.

Therefore, bagasse-based electricity could be increased by the replacement of existing boilers in the other two sugar mills with 82 bar/520°C boilers. Thus, all the bagasse power plants would be equipped with 82 bar/520°C boilers, hence increasing the total electricity generation by bagasse to 430 GWh, representing an increase of 86GWh. Thus, this amount of electricity would not be generated by power plant using Heavy Fuel Oil (HFO) as fuel. Coal is mainly used only during the intercrop season by power plants annexed to sugar mills. Given that 0.21 kg of HFO is needed to produce one kWh of electricity and produce 0.65 kg of CO_2 emissions. The savings in terms of HFO would be 18 000 tonnes representing 56 Gg of CO_2 emissions mitigated. Finally, the average electricity generated per tonne of cane will increase from 87 kWh to 109 kWh.

Scenario B: use of cane of higher fibre content

The weight of bagasse depends on the percentage of fibre content and the moisture content present in the sugar cane [25]. The higher the percentage of fibre, the higher will be the weight of bagasse, thus more steam would be produced and available for electricity production. Research is being done at the Mauritius Sugar Industry Research Institute (MSIRI), now called the Mauritius Cane Industry Authority (MCIA) for the breeding of higher fibre percent of sugar cane taking into consideration the climate and soil of Mauritius. Santchurn et al. [26] studied different types of high biomass genotypes obtainable from early generation hybrid populations of sugar cane. They found that the fibre percent of cane could be increased to 17% as compared to the present commercial varieties having a maximum fibre content of 14% with the same sugar yield. Other genotypes varieties could have up to 23% fibre content in cane- energy cane- but with lesser sugar yield. Thus, policy makers have the option of promoting the use of higher fibre cane for augmenting electricity generation with same amount of production of sugar or the use of energy cane of electricity generation at the expense of sugar manufacturing. According to Lau et al. [27], for every percent rise in fibre content in sugar cane, the electricity generated would increase by 11kWh/tc, 8 kWh/tc and 6kWh/tc when the bagasse is burnt in 82bar/520°C, 45bar/440°C and 31bar/440°C respectively. These results are in accordance with experiments done by feeding higher fibre cane in high pressure and temperature boiler in Reunion island, a French Territory nearby Mauritius [25]. Khoodaruth and Elahee [7] reported that the use of higher fibre cane could increase the amount of bagasse by 63% compared to that of present commercial canes.

Assuming that a higher fibre content cane of 4% more than the actual commercial varieties of cane is used but with more or less the same sugar yield, the electricity generation will be increased to 44kWh/tc, 32 kWh/tc and 24 kWh/tc when the bagasse is being burnt in 82bar/520°C, 45bar/440°C and 31bar/440°C respectively. Thus the total electricity generation would increase to 505GWh (representing an increase of 160GWh) assuming the total harvested area of sugar cane is same as that in 2012 [28]. About 34 000tonnes of heavy fuel would have been saved and about 104 Gg of CO_2 would be mitigated. The energy generation per tonne of cane would be 128 kWh.

Scenario C: use of cane tops and leaves as fuel in addition to bagasse in boilers

The sugar cane plant consists of stalk, root, leaves and trash. During the harvest, only the stalks are collected and transported to the mills. The tops, leaves and trash are left in the field. Deepchand and Baguant [29], worked on the feasibility of the utilization of cane tops and leaves(CTL) for the production of electricity and ethanol. They observed that for every 100 tonnes of cane harvested, 30 tonnes of CTL are left in the field. Moreover, they estimated that every tonne of CTL would generate at least 100 kWh of electricity. Beeharry [30] computed the bagasse equivalence of CTL and found that every tonne of CTL is equivalent to 0.62 tonne of bagasse because of the higher moisture content of CTL which is 68% compared to that of bagasse which is 50%. Assuming that only 50% of the CTL is collected and the rest is left in the sugar cane fields for use as fertilizers, the total amount of extra electricity produced would be 107 GWh using CTL as fuel for a cane production of 3.9M tonnes. About 69 Gg of CO_2 would be mitigated and 22 000 tonnes of Heavy Fuel Oil would not need to be consumed and imported. This will enhance the electricity generation per tonne of cane crushed to 114 kWh.

Scenario D: optimization of low pressure steam in sugar mills

Heat and electricity are the outputs of the bagasse cogeneration power plants. The low pressure and temperature heat (around 2.7 bar/130-150^{0}C) is supplied to sugar mills and refineries for production of raw and refined sugars. The consumption of steam by the sugar mills is about 350-500 tonne/tonne of cane [21], while that for the distilleries is 25 tonne/tonne of raw sugar and about 10-13 tonne for the distillery plant. Furthermore, as shown in Fig. 2, the evaporators and the vacuum pans are the highest consumers of steam in a sugar mills.

The evaporator is used to process cane juice obtained from the milling of sugar cane to syrup. The latter is then converted to sugar in vacuum pans. The process heat obtained from the power plant is used to remove water in the sugar cane juice by vaporization. The Mauritian sugar factories are equipped with the latest technology and they are indeed efficient. However, opportunities exist for the evaporating process. Sooben [32] highlighted the recent improvements in evaporating process with the falling film evaporator. The latter is a heat exchanger which may be installed before the existing set of evaporators. The falling film was initially used by the sugar beet industries. Due to its high heat transfer coefficient, falling film evaporators could be operated with very low temperature differences between the heating media and the boiling liquid. Thus, this makes it suitable for use in multi-effect evaporators. It was then adopted by the sugar cane mills. Other sugar producing countries/territories such as Reunion Islands have already adopted such technology which has contributed to a reduction of about 10% of steam for the evaporation of cane juice [32]. Thus the implementation of such technology in sugar mills in Mauritius would decrease the steam consumption in sugar mill resulting in more steam for electricity production. It is calculated that the extra electricity produced would be 26 GWh with a savings in 5000 tonnes of HFO and about 17 Gg of CO_2 would be mitigated. Finally, the electricity generation will increase to 94 kWh/tc.

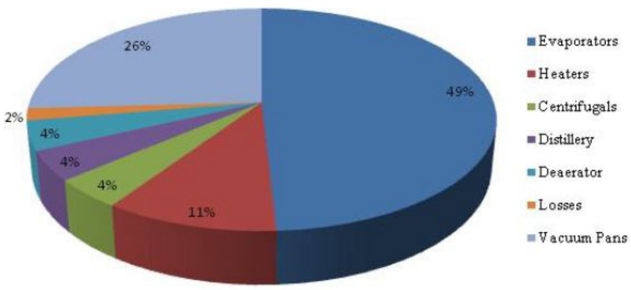

Fig. 2. Relative Steam Consumption [31]

Scenario E: A combination of scenarios A to D

Simultaneous implementation of high temperature and pressure boilers in all sugar mill, utilization of higher fibre cane, use of 50% of CTL and falling film evaporators would lead to a very efficient cogeneration power systems. The electricity generation per tonne of cane would jump to 183 kWh, the extra electricity generation would be 379 GWh . The total CO_2 emissions would be reduced to 246 Gg and about 80 000 tonnes of HFO would not be used and imported for electricity production during the harvesting period.

4.2. Multi-criteria Analysis

Multi-criteria analysis is being used to assess the 3Es, that, Economy, Environment and Ethics for the five scenarios. The criteria that are being used for this paper are as follows: energy security; capital expenditure; revenue from bagasse-based electricity; wastes disposal; health hazard risks and compliance with environmental laws. Scenario E is the best one because it is a combination of the Scenario A to D, Thus electricity generation per tonne of cane will be the optimum which will lead to less GHGs emissions and improvement in energy security. In addition, revenues obtained from sugar cane plants will be maximized. However, the capital expenditure for simultaneous implementation of these scenarios will be the highest. Furthermore, higher amount of ash disposal will cause an increased hazard risks to the employees of the cogeneration plants and to the inhabitants living nearby these plants. For Scenario A to D, a web chart is plotted as shown in Fig. 3.

Scenario A has the highest capital expenditure, replacement of existing medium temperature and pressure boilers to high pressure temperature and pressure boilers in addition to replacement of exisiting turbine cum alternators to higher capacity would need a collosal investment from the IPPs. The estimated investment is estimated to be USD 50M. Investment in falling film technology for Scenario D is only USD 2M. For scenario C, the investment is minimal as existing equipment for the loading and unloading of cane could be used to load and also transport the CTL to sugar mills. For Scenario B, the investment would be only in research and development for higher fibre cane yet under this scenario, higher revenues are expected per tonne of cane due to increase electricity generation. Any increase in revenues would make the industry viable and sustainable in terms of job security to employees of the cane sector. However, more bagasse will cause an increase in electricity generation as well as in the amount of ash that has to be disposed. This increase in ash will result in health harzards for the employees as well as the inhabitants of living nearby to ther flexi-factory. Moreover, any increase in electricity generation would increase the share of bagasse electricity in the electricity mix of Mauritius. This in turn would also decrease the total GHGs emissions for Mauritius. In 2013, the total GHGs emissions stood at 3640 Gg, of which, the electricity industries are contributing an amount of 2206 Gg, that is, 61% [17].

The implementation of these scenarios could be done in short, medium and long terms. In the short term, use of CTL as fuel in boilers could be envisaged as well as the introduction of falling film technology in sugar mills to reduce steam consumptions. Implementation of higher temperature and pressure boiler in all the power plants except those already equipped could be envisaged. In the medium term, the implementation of high pressure and temperature boilers as well as higher capacity turbine and alternators could be considered. The Government would need to provide financial support to IPPs given the huge investment in capital expenditure. But the country would benefit in terms of increased bagasse electricty thus less importation of fossil fuels and improvement in the energy security of the country. In the longerrun, the replacement of existing cane varieties with higher fibre cane is encouraged. But this would take some years for the research and development of new varieties adaptable to the local context and the replacement of existing varieties as the latter last about six years from the first ratoon.

The revenue could also increase by producing ethanol. Sultan and Khoodaruth [33] reported that if all the sugar juice is converted to ethanol, about 375 ML could be produced with the current amount of land under sugar cane cultivation. Production of ethanol will increase the sustainability of the sugar cane industry as well as the energy efficiency of the whole process [15].

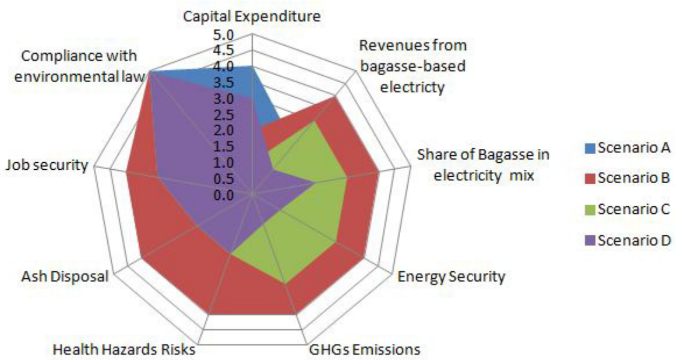

Fig. 3: Multi-criteria analysis

Conclusion

The cane industry is at a cross road. Due to the decreasing prices obtained from the sale of sugar from EU, planters are abandoning their land. To make the industry viable and sustainable, implementation of higher pressure and temperature boilers, use of higher fibre cane, utilization of CTL and optimization of low process steam are promoted. But given the huge investment in implementation of these measures, it is recommended these in short, medium and long term. This would not only increase revenues from the sugar cane crops but also would improve our energy security and decrease the total GHG emissions by 7%. In addition, the share of bagasse-based electricity would increase by 100% from the present share of 14% to expected 28%. Finally, as future works, the study of gasification of bagasse could be undertaken.

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References

[1] Dantas GA, Legey LFL, Mazzone A. Energy from sugarcane bagasse in Brazil: An assessment of the productivity and cost of different technological routes, Renewable and Sustainable Energy Reviews 2013; 21: 356–64.

[2] Evans A, Strezov V, Evans TJ. Sustainability considerations for electricity generation from biomass, Renewable and Sustainable Energy Reviews 2010; 14:1419–27.
[3] Aklilu BT, Gilani SI. Mathematical modeling and simulation of a cogeneration plant, Applied Thermal Engineering 2010; 30: 2545-54.
[4] Oh SD, Lee HJ, Jung JY, Kwak HY. Optimal planning and economic evaluation of cogeneration system, Energy 2007; 32-760–71.
[5] Srirangan K, Akawi L, Moo-Young M, Perry Chou C. Towards sustainable production of clean energy carriers from biomass resources, Applied Energy 2012; 100: 172–86.
[6] Paturau M. Histoire Economique de l'ile Maurice 2008, Port-Louis, Mauritius.
[7] Khoodaruth A, Elahee MK. Use of higher fibre cane for increasing cogenerated electricity: Policy implications for Mauritius. Utilities Policy 2013; 26: 67–75.
[8] Ministry of Agro-Industry & Fisheries. Multi Annual Adaptation Strategy Action Plan 2006–2015: Safeguarding the Future through Consensus;2006. http://agriculture.gov.mu/English/Documents/Land%20Conversion%20Unit/mass.pdf (accessed on 10.01.14.)
[9] Mashoko L, Mbohwa C,Thomas VM. Life cycle inventory of electricity cogeneration from bagasse in the South African sugar industry. Journal of Cleaner Production 2013; 39: 42-9.
[10] Elahee MK. Sustainable energy policy for small-island developing states. Utilities Policy 2011; 19: 71-9.
[11] Cherubini F, The biorefinery concept: Using biomass instead of oil for producing energy and chemicals. Energy Conversion Management 2010; 51: 1412–21.
[12] Nguyen TLT, Hermansen JE, Sagisaka M. Fossil energy savings potential of sugar cane bio-energy systems, Applied Energy 2009; 86 :132–9.
[13] Faaij APC. Bio-energy in Europe: changing technology choices. Energy Policy 2006: 34: 322–42.
[14] Demirbas MF, Balat M, Balat H. Potential contribution of biomass to the sustainable energy development. Energy Conversion Management 2009; 50:1746–60.
[15] Dias MOS, Junqueira TL, Cavalett O, Pavanello LG, Cunha MP, Jesus CDF, Filho RM, Bonomi A. Biorefineries for the production of first and second generation ethanol and electricity from sugarcane, Applied Energy 2013; 109: 72–8.
[16] Starfelt F, Thorin E, Dotzauer E, Yan J. (2010). Performance evaluation of adding ethanol production into an existing combined heat and power plant, Bioresources Technology 2010; 101: 613–18.
[17] Statistics Mauritius, Republic of Mauritius. Digest of Environment Statistics 2012; p.49.
[18] Çakir U, Çomakli K, Yüksel F. The role of cogeneration systems in sustainability of energy, Energy Conversion Management 2012; 63: 196–202.
[19] Chauhan MK, Chaudhary VS, Kumar S, Samar. Life cycle assessment of sugar industry: A review, Renewable Sustainable Energy Reviews 2011; 15: 3445–53.
[20] Autrey JC. Mauritius Future Orientations of Research and Development for Sugar Cane Industries of ACP States , ACP Sugar Research Programme Mid-Term Review Workshop, MSIRI 2012. www.acpsrp.eu/sites /default/files/documents /pwp/04%20Future%20actions %20SRP%20ACP.pptx (accessed 05 01 14).
[21] Seebaluck V, Sobhanbabu PRK. Sugar cane processing and energy generation from fibre resources, Bioenergy for Sustainable Development and International Competitiveness: The Bioenergy for Sustainable Development and International Competitiveness: The Role of Sugar Cane in Africa, Routledge, UK; 2011. p. 100-25.
[22] Chatzimouratidis AL, Pilavachi PA. Technological, economic and sustainability evaluation of power plants using the Analytic Hierarchy Process. Energy Policy 2009; 37: 778-87.
[23] Ministry of Renewable Energy and Public Utilities, Republic of Mauritius. Long term energy strategy 2009–2025; 2009
[24] Statistics Mauritius, Republic of Mauritius. Digest of Energy and Water Statistics 2012; p. 46.
[25] Corcodel L, Roussel C, Decloux M. Energy content: A new approach to cane evaluation, International Sugar Journal 2011; 113: 782-785.
[26] Santchurn D, Ramdoyal K, Badaloo MGH, Labuschagne MT. From sugar industry to cane industry: Evaluation and simultaneous selection of different types of high biomass canes, Biomass and Bioenergy 2014; 61: 82-92.
[27] Lau AF, Kong Win Chang KTKF, Gunness D. (2005). An integral approach to evaluate the performance of bagasse co-generation plants, Proceedings of International Society of Sugar Cane Technology 2005; 25: 385–93.
[28] Statistics Mauritius, Republic of Mauritius. Digest of Agricultural Statistics 2011; p. 40.
[29] Deepchand K, Baguant J. Utilisation of cane tops and leaves for energy and food — an integrated system, Biomass 1985; 7: 215-23.
[30] Beeharry RP. Strategies for augmenting sugarcane biomass availability for power production in Mauritius, Biomass and Bioenergy 2001; 20: 421-29.
[31] Bheekun AK, Choo Fon JY. Energy monitoring and power saving plan, Final Year Thesis, University of Mauritius; 2010.
[32] Sooben S. Optimization of the use of Low Pressure Steam at Omnicane Sugar Factory, Final Year Thesis, University of Mauritius; 2013.
[33] Sultan R, Khoodaruth A. An assessment of energy balance from sugar-based ethanol for fuel-saving and climate policy – the case of an island economy, International Journal of Environment and Sustainable Development 2013; 12: 324-40.